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Palaeoecological study of Pyrenean lowland fir forests: Exploring mid–late Holocene history of *Abies alba* in Montbrun (Ariège, France)

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A B S T R A C T

Fir (*Abies alba* Mill.) occupies an important place in the Pyrenean context, where the species finds its optimal conditions in this mountain zone (800–1800 m a.s.l.). In the Pyrenees, the fir woods of Volvestre (Ariège, France) are of particular interest because of two peculiarities of its location: its northern latitude with respect to the usual location of fir in the Pyrenean axis, and its lower altitude (330–440 m a.s.l.). This has given rise to various theories, some considering the silver fir forests as a glacial relic and others pointing to anthropogenic interference and possible plantings during the Middle Ages. Pedoanthracological and palynological studies have been performed to establish the origin and history of this ancient forest, and both approaches show an ancient anthropized landscape with a continuous presence of *Abies alba* throughout the mid- and late-Holocene. The fir woodlands of Volvestre are testimonies to the ancient and significant presence of fir on the northeast slope of the Pyrenees and the current suitability of this species for lowland areas. Pedoanthracological sampling inside the forest has shown differences in vegetation dynamics at different valley points (north slope, south slope, and valley bottom).

1. Introduction

Abies Alba Mill. currently extends throughout the principal mountain regions of Central and Southern Europe. In the Pyrenees, the fir tree appears to find optimal conditions in the mountain and subalpine range, between 800 m and 1800 m above sea level, on north-facing slopes.

Previous research has shown that the distribution of *Abies alba* in Europe is more limited at present than during the middle Holocene, when it was dominant in the mountain areas and even in the lower lands (Tinner et al., 1999; Carcaillet and Muller, 2005; Tinner and Lotter, 2006; Wick and Möll, 2006; Tinner et al., 2013). In the Pyrenees, palynological studies have confirmed this pattern (Jalut et al., 1988; Pèlachs et al., 2009; Galop et al., 2013). In addition, various models of the presence of Pyrenean fir were recently carried out from the topoclimatic point of view based on current climatic conditions of fir populations (Alba-Sánchez et al., 2009, 2010; Serra-Diaz et al., 2012). These models highlighted the more limited current extension of the fir tree in the Pyrenees than was expected (Fig. 1).

Topoclimatic spatial distribution models have been developed for the Pyrenees, based on current climate conditions (Alba-Sánchez et al., 2009, 2010; Serra-Diaz et al., 2012). Compared to the potential distribution in the models, the current extent of *Abies* in the Pyrenees is more limited than expected, occupying 30% of the optimal potential area and a wider altitudinal interval (Alba-Sánchez et al., 2009). A similar trend was found at a more general level for southeastern Europe (Tinner et al., 2013) (see Fig. 2).

Recent phylogenetic studies show that the Pyrenean populations of Abies have strong genetic originality, pointing to their long-term isolation from the other European populations during the Quaternary glacial periods (Konnert and Bergmann, 1995; Fady et al., 1999; Terhürne-Berson et al., 2004; Liepelt et al., 2009). However, contact with the alpine settlements or with populations in the southeast of France (Pèlachs et al., 2010) cannot be excluded. Given the current data, it is even more difficult to say which areas

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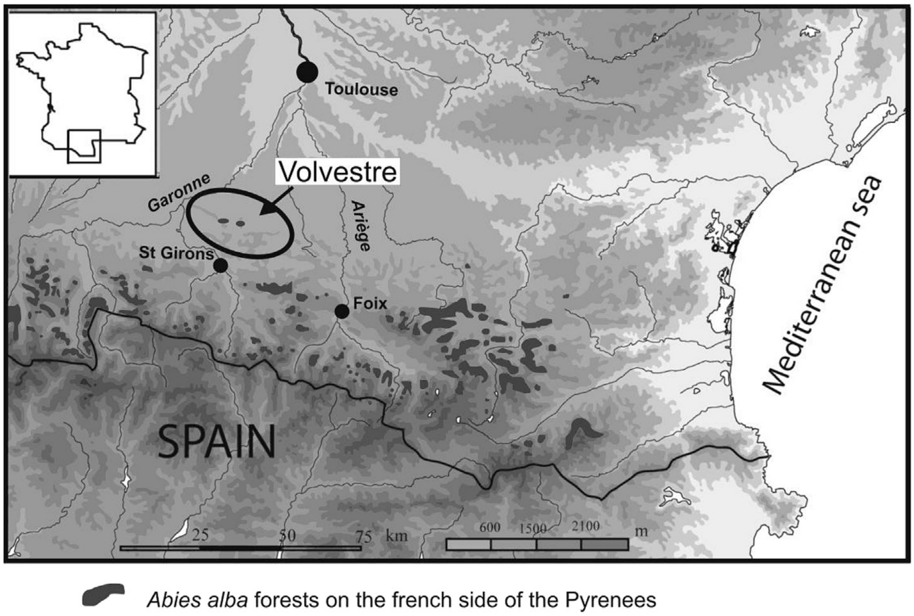

Fig. 1. Location of the Volvestre region, showing the forests of Ste-Croix-Volvestre and Montbrun-Bocage. Data: IFN, Institu Nacional de l'Information Géographique et Forestière.

would have been glacial refuges and which were the pathways of postglacial migration. However, the data indicate that fir colonized both sides of the Pyrenean massif from east to west (Jalut et al., 1996; Esteban et al., 2003; Pèlachs, 2005). On the south Pyrenean slope, the first early Holocene presence was in interior valleys of the southeast Pyrenean foothills (Pérez-Obiols, 1988; Burjachs and Julià, 1994; Pérez-Obiols and Julià, 1994; Burjachs, 1994). On the north side, the first *Abies* palynological data are found in Nohèdes, at 60 km from the Mediterranean coast, towards 9300 cal BP (Reille and Loewe, 1993). However, the expansion towards the northwest of the Pyrenees occurs after the climatically favourable event (of the 8200 cal BP type) that occurred between 7300–6600 cal BP and 3550–3200 cal BP (Galop and Jalut, 1994; Galop, 1998).

The current distribution of the fir tree cannot be explained solely by environmental factors (climate, soil, topography); therefore, it is necessary to take into account the anthropic factors. Over the long term, the palynological data show anthropic determinism of the dynamics of fir woodlands on both sides of the Pyrenees during the second half of the Holocene (Galop and Jalut, 1994; Galop, 1998; Pèlachs, 2005; Ejarque et al., 2010). At the scale of the last two millennia, the history and spatial distribution of fir woodlands has been characterized in many areas, in particular in the eastern half of the range. The impact of iron metallurgy and related charcoal production was a determining factor for the evolution of the forests in most valleys of Ariège and Catalonia, and provoked the near disappearance of the fir

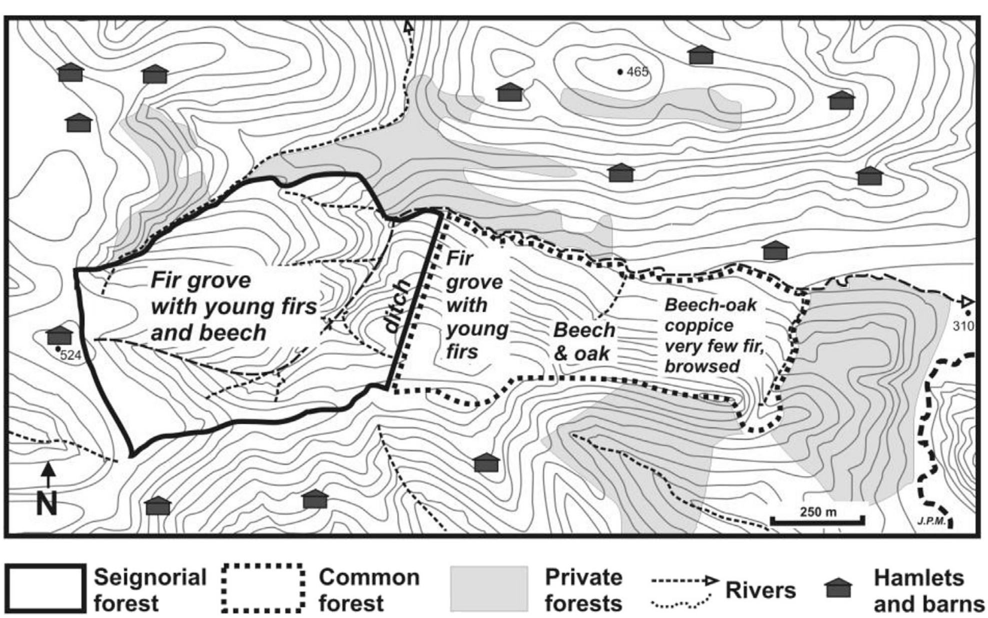

Fig. 2. The forest of Montbrun at the end of 18th century and first half of 19th century. Sources: archives of Montbrun-Bocage (Archives of Haute-Garonne, 2E1239, 2E2354, 2E1961); topographic map of 1849 (IGNF_SCAN_EM_40K_1-0__2009-07-02__SCAN_4EM242SO_40K_1849).

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tree, replaced by beech and oak coppices or pastures. These activities and their environmental impacts were determined by palynological or anthracological kiln site analysis on both sides of the Pyrenees (Bonhôte and Fruhauf, 1990; Galop and Jalut, 1994; Bonhôte, 1998; Bonhôte et al., 2002; Pèlachs et al., 2009). It could also highlight an early role such as during the Middle Ages of the management of fir groves by communities or landlords, in order to preserve a disappearing resource (Bonhôte, 1998; Dubois and Métailié, 2001; Métailié, 2006). In the regions where rafting was possible (high valley of the Aude; the Garonne valley), the fir forests were preserved because of their interest for the navy and for lumber, and the possibility of trading along the Garonne river (Fruhauf, 1980; Métailié et al., 1989). However, in spite of this very strong human pressure since the Neolithic era, one cannot exclude the influence of climatic oscillations to explain the distribution of the species. There is a frequent superposition of climate and anthropic changes that makes it difficult to determine where one influence starts and another ends (Tinner et al., 1999).

Within this general framework, the fir woodlands of the Volvestre area constitute an anomaly and a very good example of the multiple knowledge gaps about the fir tree that exist in the Pyrenean context (Blanco et al., 1997). These silver fir forests are distant from the chain in the Piedmont hills, and disjunct from the current mountain fir forests (Fig. 1). In addition, the altitude (350–450 m) that characterizes these fir forests is the lowest elevation in the southern part of France. This particular location in the Pyrenean range gives rise to various hypotheses. One generally regards these woodlands as a relic inherited from a glacial refuge or from postglacial-way migrations. Others interpret their presence as the result of planting trees at the initiative of an abbey built in Sainte-Croix-Volvestre ("Holy Cross") during the 12th century, which received the forest in donation and remained the landlord until the French Revolution of 1789 (Gonin et al., 2012; Cunill et al., 2014). Until now, no research had been undertaken to test these hypotheses. Due to the importance of the fir tree in Pyrenean forestry and the questions about its local future in the context of global climate change, an interdisciplinary research program was set up to study the genetics and the dynamics of the Pyrenean fir forests, particularly in the Volvestre region (Gonin et al., 2012). They provide an exemplary site for the application of an interdisciplinary methodology to explore environmental history: What information can these forests give us on the postglacial migrations of the species? Is their origin natural or anthropic? Which is the ancient and current distribution range of fir in the Pyrenees? What is the historical relationship between these forests and the environmental history of the area? Can we reconstruct and spatialize the history of the land management in the area with pedoanthracology?

To answer these questions, a multiproxy approach was chosen for the present study, drawing from pedoanthracology, palynology, historical sources, and phytogeographical and geomorphological study of the area. Each of these methodologies contributes to a more thorough understanding of the environmental geohistory, providing different and complementary insights. In this paper, we present the pedoanthracological findings, supported by preliminary palynological results.

Soil charcoal analysis allows us to determine with great spatial precision the vegetation dynamics in the various geofacies identified within the same forest. It permits the precise localization of the dynamics assessed with palynology at a wider scale. On the other hand, palynology provides a long chronology and an overall context of the vegetation dynamics not limited to woody plants, highlighting the impact of agro-pastoral colonization and fires (Robin et al., 2011, Cunill et al., 2013). The results of both methodologies can also be connected to the historical data on forest management practices.

2. Study area

Volvestre is a relatively marginal area in the Pyrenean range. It was the object of restricted research on vegetation (Gonin, 1993; Savoie, 1995) in comparison with the upper valleys, which attracted the naturalists since the 18th century. Some ancient studies on geomorphology are available (Goron, 1942; Taillefer, 1951) but the historians, in particular, never worked on the problem of the forest. No researches on paleoecology or forest history were undertaken before the research project implemented in 2009 (Gonin et al., 2012), which made it possible to look further into ecological data gathered on the area and to develop a multi-proxy study on the long history of the environment.

2.1. Description of the region

The hills of the Volvestre area are located in the piedmont on the northern slope of the Pyrenees (Fig. 1). This geological region is composed of limestone, marlstone, and sandstone of Jurassic, Cretaceous, and Eocene origin, with folds oriented east to west, between 300 and 600 m a.s.l., constituting the "Small Pyrenees" (BRGM, 1979). The area is also characterized by the presence of Plio-Quaternary alluvia surmounting the hills, which form terraces that dominate the valleys and left many colluvial deposits on the slopes. Thus, there exists an alternation of calcic brown soils on limestone, of compact argillaceous soils on the marls, of deep sandy-argillaceous soils on the weathered sandstones, and of acidic and stony soils on the Plio-Quaternary alluvia and colluvial deposits (Goron, 1942; Taillefer, 1951; Hubschman, 1975; BRGM, 1979).

The climate is moderate oceanic with an average annual temperature of 11.9 °C and average annual precipitation of 900 mm. In summer, average temperature is 21 °C and there is no summer drought (Gonin et al., 2012). The vegetation is mainly dominated by broadleaved forest trees, such as oaks (*Quercus petraea* (Matt.) Liebl., *Quercus pubescens* Willd., *Quercus robur* L.) along with beech (*Fagus sylvatica* L.), chestnut (*Castanea s*ativa Miller), and a set of very diversified trees and shrubs (*Fraxinus excelsior* L., *Tilia cordata* Mill., *Betula pubescens* Erhr., *Prunus avium* L., *Carpinus betulus* L., *Salix caprea* L., *Acer campestre* L., *Alnus glutinosa* L., *Ligustrum vulgare* L., *Crataegus monogyna* Jacq., *Juniperus communis* L., *Ilex aquifolium* L., *Pyrus malus* L. *Ruscus aculeatus* L., *Rosa sp*., *Calluna vulgaris* L., *Vaccinium myrtillus* L., *Pteridium aquilinum* (L) Kuhn). On the sunny slopes of the calcareous hills, the holm oak (*Quercus ilex* L.) can be found, accompanied by Mediterranean shrubs (*Lavandula angustifolia* Mill., *Thymus vul*garis L., *Genista scorpius* L., etc) (Gonin, 1993; Savoie, 1995). High fir forests are found mainly in two areas, Sainte-Croix-Volvestre (200 ha, ancient abbey forest, 120 ha of fir groves) and Montbrun-Bocage (140 ha, ancient seignorial and common forest, 17 ha of fir groves). However, in the Volvestre area the fir is dispersed over nearly 1500 ha (National Forest Inventory data). Historically, since at least the Middle Ages, all the forests of the Volvestre area were managed as coppice, sometimes as coppice with standards. The fir woodlands of Sainte-Croix and Montbrun were managed to meet the timber demand for buildings and navy ships. The rate of afforestation of the Volvestre area was always high and reached 30%–40% in the 19th century, at the time of the strongest decline in forest cover. This rate currently ranges from 40% to 80%, according to the *communes* (townships), because of the natural increase at the expense of fallowed fields and pastures, but also due to the planting of coniferous trees in the second half of the 20th century (*Pinus sylvestris*, L.; *Pinus nigra*, R. Legay; *Pseudotsuga* *menziessi*, *(Mirb.) Franco*; and *Picea abies*, *(L.) H. Karst*) (National Forest Inventory data).

2.2. Forest of Montbrun-Bocage

The forest of Montbrun-Bocage is located in a small east–west valley excavated into the anticline of the Plantaurel and Petites Pyrénées that skirts the northern slope of the central Pyrenees. The rocks are mainly sandstone and marlstone of Maastrichtian (upper Cretaceous) (BRGM, 1979), covered with thick weathering and colluvium that were notched in the upper part of the watershed by deep ravines. The altitude ranges from 310 m a.s.l. downstream to the east to 524 m a.s.l. upstream in the west. The ridges are covered by the remains of a Plio-Quaternary alluvial cone (Taillefer, 1951), where pebbles abound. The bottom of the main thalweg is filled by alluvial sedimentation that can reach 3–4 m deep, with pebbles from the upper alluvial terraces.

The forest vegetation is mainly composed by oak, beech, chestnut, and fir. The fir woodlands have been managed since at least the 18th century to obtain groves and timber production for construction projects or masts for navy ships, while beech, oaks, and chestnut were managed in coppice, or coppice with standards, for local uses and firewood. The forest is mainly located on the north- and east-facing slopes; the sunny slope was mainly pastures and agricultural terraces until the 1950s. However, small parcels of woodland were always maintained on private lands.

The earliest precise historical sources (e.g., forest survey of 1746, archives of the revolutionary period, topographic map of 1849) attest that the limits of the forest, which is surrounded by ancient hamlets and barns, have changed little since the 17th century. At the end of the 18th century, the "forest of Montbrun-Bocage" included a communal forest of 66 ha (beech–fir groves and coppices of oak, beech, and chestnut) in the eastern part and a seignorial forest of 77 ha (beech–fir groves) in the west (see Fig. 2). The seignorial forest was sold off piecemeal during the first half of the 19th century, while 40 ha of the communal forest was sold in 1861, the commune keeping only the broadleaved coppice (27 ha). The privately held forest areas have changed owners often up until the present, which led to overexploitation of the fir tree. Today, the fir groves cover only a limited surface of the entire forest (17 ha). The remarkable vitality of *Abies alba* is evidenced in the archives ("young firs are swarming"), and today most of the woodlands are experiencing very active regeneration of fir. The major current landscape change is the spontaneous or artificial afforestation of agricultural lands since 1960–70, a consequence of their abandonment (Fig. 3).

3. Materials and methods

3.1. Pedoanthracology analysis

In order to get an overall history as well as spatial interpretation within the valley, a multi-sampling strategy was used to determine the local diversity at both the bioclimatic and anthropic management level. Two sampling points were located in the pedological context in woodlands of the south-facing (Montbrun 3) and north-facing (Montbrun 2) slopes of the valley (Fig. 1). A third sampling point was selected in a pedosedimentary context (Montbrun 1), in the alluvial terrace that fills the lower part of the valley. The objective was to obtain a representative sampling of vegetation of the whole watershed, covering current forested areas and agricultural fields(see Fig. 3).

The samples were extracted by digging three holes 190 cm deep for sedimentary samples and 110 cm and 100 cm deep for forest soils. Isolation, quantification, and identification of soil charcoals were based on a procedure previously published by Talon et al. (1998). Anthracomass was calculated on the basis of the mass of charcoal fragments larger than 0.8 mm.

Taxonomic analysis was done for a maximum of 100 charcoal pieces (including indeterminate charcoal and vitrified charcoal) per layer of sampling when the charcoal quantity allowed. To avoid bias due to possible variability in fragmentation, depending on the type of anatomic structure and/or state of conservation, the 100 charcoal pieces were randomly selected and equitably divided into three

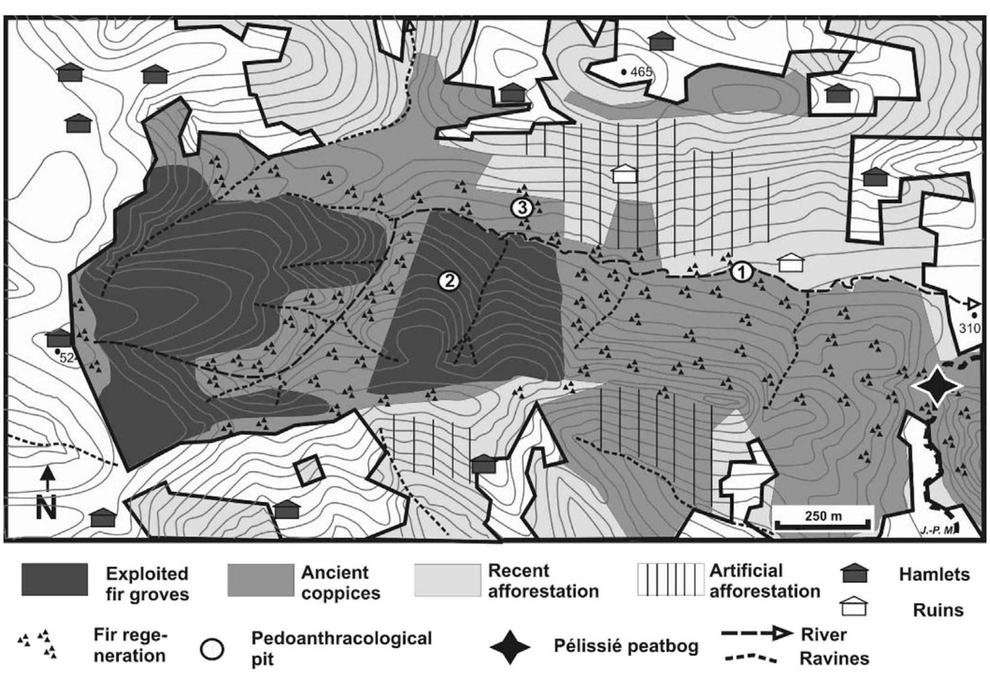

Fig. 3. Current vegetation of the forest of Montbrun (aerial photographs and ground plotting).

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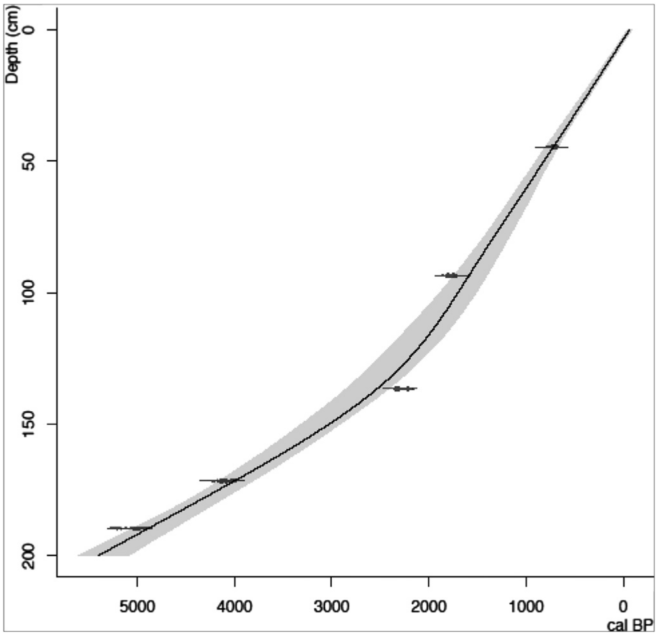

Fig. 4. Age–depth model of the Pelissie sequence based on smooth spline age-model with a default smoothing 0.3.

classes by size: >5 mm, 5–2 mm, and 2–0.8 m when the quantity of each charcoal size allowed it. To identify the charcoal fragments (n = 1864), we used an Olympus BX 51 episcopic microscope (100×, 200×, and 500×). Taxa were determined with the help of an atlas of the anatomy of woody plants (Schweingruber, 1982, 1990; Vernet et al., 2001) and the charred wood reference collection of the GEODE laboratory (University of Toulouse II-Jean-Jaurès).

From the group of separated charcoals, a total of 15 samples were selected for carbon-14 dating by Accelerator Mass Spectrometry (14C-AMS) in the Beta Analytic laboratory (Miami, Florida, USA) and Poznan Radiocarbon Laboratory (Poznan, Poland). The radiocarbon ages were calibrated using the Oxcal program, version 4.2, based on the Intcal13.14c database (Reimer et al., 2013) and with a standard deviation of 2 sigma (95% probability).

3.2. Palynology methods

One core sample (PELIS) was taken with a Russian peat sampler (GIK type, 50 cm length, 8 cm in diameter). The sampling point was located at 312 m a.s.l. in a small peat area at Pélissié, an alluvial terrace along the Paris stream. Four overlapping 50-cm cores were obtained. Five vegetal macroremains samples were selected for 14C-AMS dating (Table 1). The age model was developed using Clam 2.2 and R 2.11.0 (Blaauw, 2010). We chose a smooth spline age-model with a default smoothing of 0.3 (see Fig. 4).

Table 1
Radiocarbon dates for the sediment cores from the Pélissié peat bogs; calibration: Clam 2.0 model (Blaauw, 2010) with calibration curve IntCal13.14C (CC = 1) from Reimer et al. (2013).

Sample	Laboratory code	Age ^{14}C	Material	Calibration (cal BP)
Pelis 44-45	Beta-323064	790 ± 30	Wood	672–760
Pelis 93-94	Beta-323061	1840 ± 30	Wood	1709–1864
Pelis 136-135	Beta-347643	2290 ± 30	Wood	2164–2353
Pelis 171-172	Beta-339973	3740 ± 30	Needle fir	3985–4223
Pelis 189-190	Beta-339974	4430 ± 30	Needle fir	4876–5274

For pollen analysis, 1 cm^3 subsamples were taken at 5 cm intervals. Pollen preparation followed standard methods using treatment with 10% KOH (35 mn), HF (24 h), sieving at 250 μm and acetolysis, and final mounting in glycerin (Faegri and Iversen, 1989). A minimum of 400 terrestrial pollen grains were counted in each sample.

Alnus and *Cyperaceae* were excluded from the pollen sum to avoid over-representation of aquatic and local taxa. All pollen types were defined according to Faegri and Iversen (1989) and Beug (2004), although some identification required the use of pollen atlases (Reille, 1992–98) or pollen reference collections from the GEODE laboratory (University of Toulouse II-Jean-Jaurès).

4. Results

4.1. Pedoanthracology

Soil sample analysis showed that anthracomass was present at all sampling points, but with high variability in the results (Fig. 5). In the Montbrun-Bocage forest, we observed a specific anthracomass of about 1500 mg/kg at the Montbrun1 sampling site, localized in the lower layers of the profile but above the gravel layer. This was the highest value found. In the Montbrun-Bocage forest, we observed a specific anthracomass of about 1500 mg/kg at the Montbrun1 sampling site, localized in the lower layers of the profile but above the gravel layer. This was the highest value found. Below the gravel layer, we found a minimal quantity of charcoals. At higher levels, the charcoal mass decreased toward the surface, stabilizing at about 200 g/kg at 70 cm depth. At the two sampling points on the forest soil, the highest numbers of charcoals were concentrated at the two layers closest to the surface (0–40 cm depth). Anthracomass levels were lowest at the deepest strata. The lowest values at these sites were observed at Montbrun3, where they never exceeded 65 mg/kg and at a certain intermediate level the charcoals disappear, and at Croix3, where we found values below 10 mg/kg. It is interesting that these very low values correspond to south-facing slope sites.

The 1895 charcoals identified contained a large variety of arboreal taxa in the valley (see Table 2), with the majority being *Fagus sylvatica*, *Quercus*/*Castanea*, and *Abies*. These taxa appeared at all sampling points. Another species with a larger presence in the profiles was *Juniperus*, followed by smaller amounts of arboreal taxa related to riverbanks *(Alnus*, *Salix*, *Populus)* and heterogeneous taxa such as *Corylus*, *Prunus*, *Maloideae*, *Rosa*, and *Ulmus*.

At Montbrun1, we identified *Abies* at almost all levels of the profile, although its presence was minimal, reaching 20% of the identified anthracomass only at the base of the profile. The *Quercus*/*Castanea* group constituted the majority of this profile and *Fagus* has an important but variable role. The presence of riverbank species such as willows differentiates this sampling point.

At Montbrun2 *Abies* constituted about 40% of the anthracomass at the base and *Quercus* and *Fagus* took over at higher levels. In this transition, *Juniperus* eventually became the major species, with values of about 20% at level IV.

The sampling point on the sunny slope, Montbrun3, was notable for the low quantity of anthracomass, the high level of vitrification, and the poor condition of the anatomic structure of the charcoal. At the higher levels we identified forest species common to all three sampling points (*Abies* or *Quercus* but not *Fagus*), and shrub taxa (*Maloideae*) present only in this profile.

The 15 radiocarbon dates ranged from the Neolithic to Modern (Table 3). Following the radiocarbon chronology, fire episodes can be dated during early Neolithic (6900–6300 cal BP), Bronze Age (3900–3200 cal BP), Antiquity-Early Middle Age (1850–1600 cal

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Table 2
Results per sample point and point level of taxonomic identification (mg).

		Abies alba	*Fagus sylvatica*	Quercus sp	Quercus/ Castanea	Alnus sp	Juniperus sp	Betulaceae (Corylus/ Alnus)	Corylus	Salix	Populus	Salix/ Populus	Prunus	Pinus	Ulmus	Maloideae/ Rosaceae	Rosa sp	Conifer	Angiosperm	Vitrified	Unidentified	Total analysed (mg)	Total analysed (n)
Montbrun 1	I	2	545	75	160		122	2		41	2							80	8	69	39	**1145**	100
	II	26	379	254	151		17	21	8		2									52	37	**947**	101
	III	10	148	416	334															37	93	**1041**	100
	IV	9	46	198	187		6							3					2	20	43	**541**	100
	V	6	9	153	165						2									12	63	**410**	100
	VI	20	177	215	243														3	30	16	**704**	121
	VII	8	76	434	541															3		**1062**	123
	VIII		867	1260	933															88	98	**3246**	139
	IX	16	2032	805	856	422		30							3			7			18	**4189**	190
	X	**18**	**55**	**107**	**26**		**8**	**8**	**3**									**6**		**134**	**8**	**373**	106
	XI	**17**		**9**	**32**		**3**									**13**		**4**	**5**	**3**		**86**	52
Montrun 2	V	8	559	188	243		21											11	36	94		1160	105
	IV	184	451	425	286		42						27						9	34	99	1557	100
	III	25	184	402	70		11		5		11							10	13	2	30	763	108
	II	79	31		53		33					2						2		9	5	214	102
	I	136	16		20		4		3			7				4	4	82		31	7	314	101
Montbrun 3	I	2		135	45								9							2		193	78
	II	7		3	1		2						3			3			6		8	33	55
	III																			1	1	2	4
	IV																						0
	V																		1	1		2	3
	VI																		**3**		**4**	7	7

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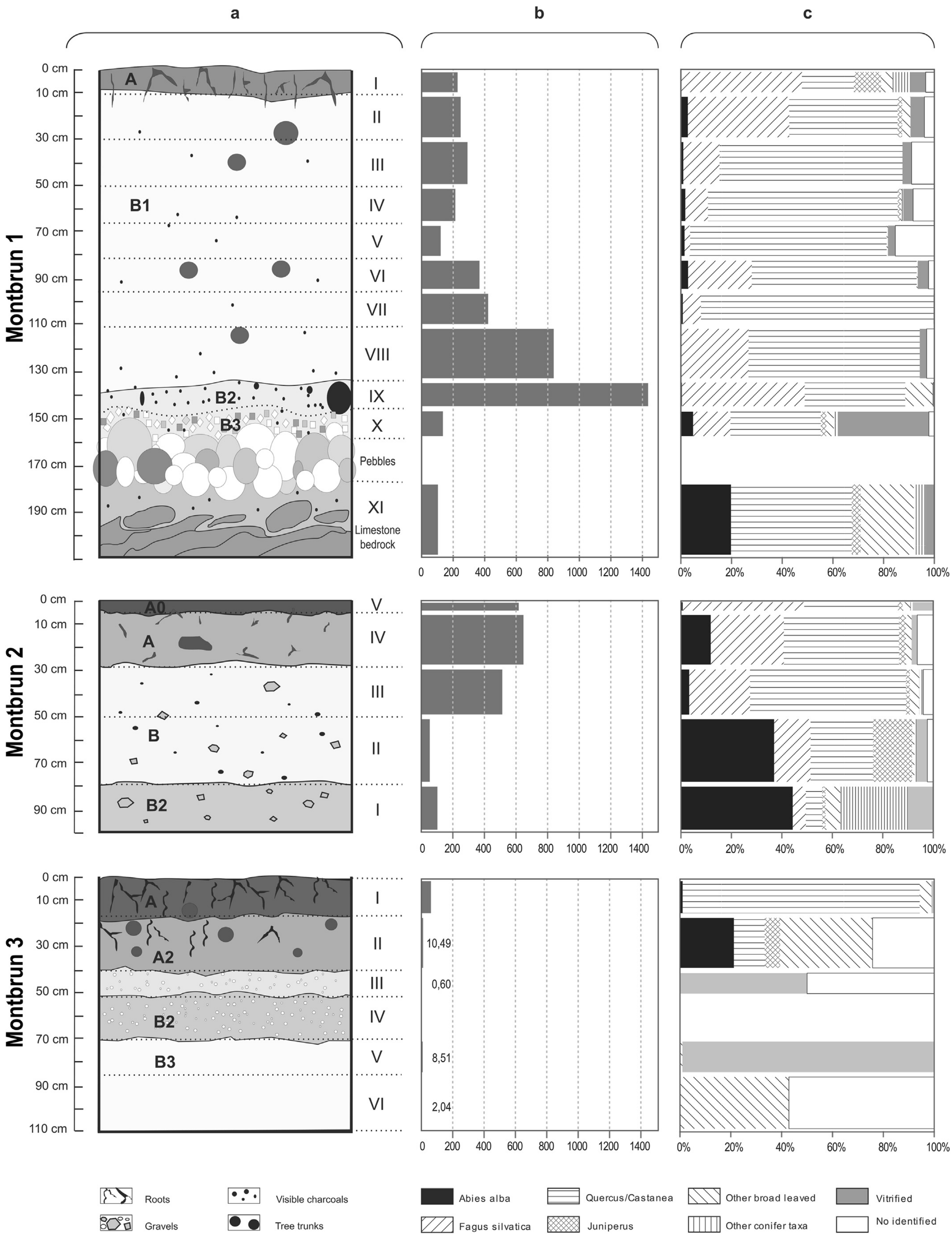

Fig. 5. Results per level of the three sample points of **a** soil profile; **b** specific anthracomass per profile (mg/kg); **c** proportion of specific anthracomass per identified taxon (%).

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BP), and Medieval-Modern (900–300 cal BP) periods. The last period, with the largest number of dates (9), can be subdivided into the 10th–14th centuries and 15th–17th centuries (Fig. 6).

Table 3
Radiocarbon dating of soil charcoals, classified by site and depth calibrated using the calibration curve of OxCal 4.2 (Bronk Ramsey, 2009).

Sample point	Deep (cm)	Code	Laboratory code	Age ^{14}C	Calibrated date (cal BP)
Montbrun 1	30–50	M1IIIFAGUS	Poz-60280	300 ± 30 BP	461–296
Montbrun 1	75–95	M1VIABIES	Poz-60281	760 ± 30	731–666
Montbrun 1	50–70	M1IVABIES	Poz-60282	340 ± 30	481–311
Montbrun 1	95–110	M1VIIQUERCUS	Poz-60287	810 ± 40	790–674
Montbrun 1	135–145	M1IXABIES	Beta-323065	870 ± 30	905–701
Montbrun 1	145–160	M1XABIES	Beta-337801	3560 ± 30	3965–3724
Montbrun 1	145–160	M1XFAGUS	Beta-337802	670 ± 30	677–559
Montbrun 1	180–200	M1XIABIES	Beta-337803	1850 ± 30	1865–1715
Montrbun 1	180–200	M1XIQUERCAST	Beta-337804	850 ± 30	898–690
Montbrun 2	10–30	M2IVABIES	Poz-60283	310 ± 30	465–301
Montbrun 2	30–50	M2IIIQUERCUS	Poz-60284	295 ± 30	460–291
Montbrun 2	50–80	MONTBRUN2-1	Poz-56965	1770 ± 35	1814–1573
Montbrun 2	80–100	MONTBRUN2-2	Poz-56966	1780 ± 25	1810–1618
Montbrun 3	20–40	M3IIQUERCUS	Poz-60285	5820 ± 110	6905–6356
Montbrun 3	70–83	M3VABIES	Poz-60286	3170 ± 50	3550–3246

In the pedosedimentary profile of Montbrun1, we found a broad chronological span, but on the valley slopes we observed temporally opposite dates. Montbrun3 offered the oldest dates (Neolithic and Bronze Age) and Montbrun2 yielded only charcoals from Antiquity and the Medieval period.

4.2. Palynology

The pollen diagram (Fig. 7) allowed us to describe the different zones and observe the major phases of the site's vegetation history.

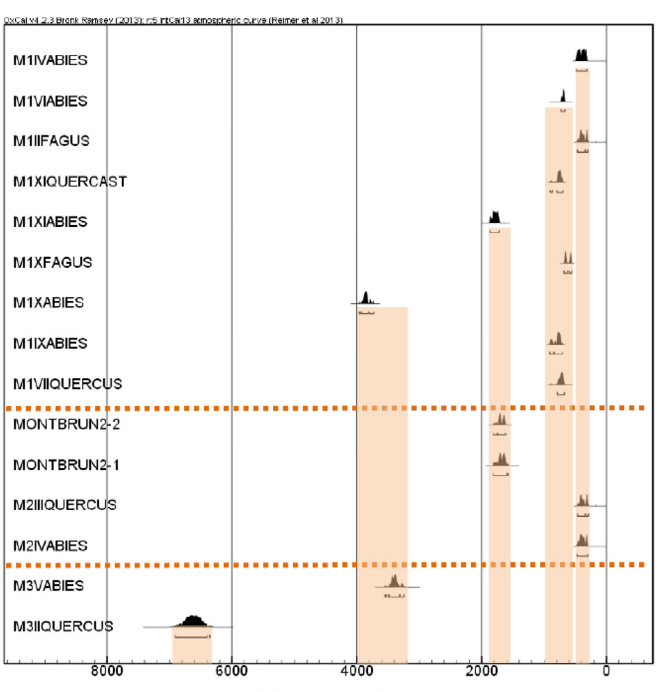

Fig. 6. Temporal distribution of 15 dated charcoals.

Several arboreal species are characteristic of the base of the pollen diagram (Phase [P]-1, 5300–4100 cal BP). *Abies* played a key role in this period, and these values are the highest in the profile. Forest changes defined phase P2 (4100–2900 cal BP). As *Abies* declined, *Fagus* arrived and quickly gained importance. Other species related to humid environments (*Fraxinus, Corylus, Alnus*) also increased during this period. Relative stability reigned during P3 and P4 (2900–1800 cal BP), with the stabilization or return of most of the arboreal species. This trend changed at the end of P4 and beginning of P5 (1800–1200 Cal BP), when all arboreal species except *Corylus* decreased dramatically. At the same time, herbaceous plants such as *Poaceae* or *Plantago* increased. This is also the point at which we began to find significant levels of Cerealia and *Secale*. The last major period of change was observed during P5b (1200–1000 cal BP) and P6 (1000–400 cal BP). The arboreal record generally decreased and only *Juglans* and *Castanea* escaped the trend. At this point, indicators of anthropic activity related to agriculture or grazing reached maximum values.

5. Discussion

The major result obtained in the present study was that pedoanthracological and palynological data prove the natural origin of the fir forests of Montbrun, and thereby contradict the hypothesis of the anthropogenic origin of this forest, which supposedly was planted during the Medieval period. In the Montbrun 1 pedoanthracological record, the oldest *Abies* charcoals were dated from the Bronze Age (3965–3724 cal BP) and at the lower level of the pollen diagram (5300 cal BP) *Abies* contributed a large part of the arboreal pollen. In addition, we know it was a local forest because fir needles and stomata were found in the same part of the sedimentary column. Nonetheless, this natural origin of the fir forest is not disconnected from a long history of human activity in this area.

5.1. Palaeoenvironmental history of the Montbrun region

The earliest charcoal dating is from the Neolithic (6905–6356 cal BP), but it is impossible to know if it results from an anthropic process or not. However, palaeoecological research in the central Pyrenean foothills (Reille and Andrieu, 1995; Rius et al., 2009) has shown clear indications of initial agricultural activity and intensification of grazing activity during this period. In addition, some authors have defended a synchronicity of fires at the macro level during the first half of the Holocene that could be due mainly to climate forcing (Rius et al., 2011, 2012). The fact that the dated charcoal was found only at one place in the valley and on the sunny slope leads us to consider a possible human action related to taking advantage of the location with the best microclimate in the valley for crops or livestock activities.

The pollen diagram provides data beginning from 5300 cal BP, showing a mixed woodland of *Quercus*, *Corylus*, or *Tilia*, where *Abies* was important at the local scale. The pollen concentration and the presence of stomatas and macroremains suggest a local fir forest.

However, this forest vegetation began to change slightly towards 4300 cal BP and more intensely after 3800 cal BP. At the forest level, *Abies* began to decrease at the same time that *Fagus* began its expansion. Simultaneously, species such as *Alnus* and *Corylus* also increased their presence. Despite a climatic change that occurred throughout the Pyrenees at this time, linked to increased humidity (Jalut et al., 1996), the increase in these species is more related to the presence of Riparian vegetation in the sampling area or to anthropic clearings than to climate change.

There were other changes during this period. The charcoals on the valley floor and the sunny slope indicate a fire phase from 3900

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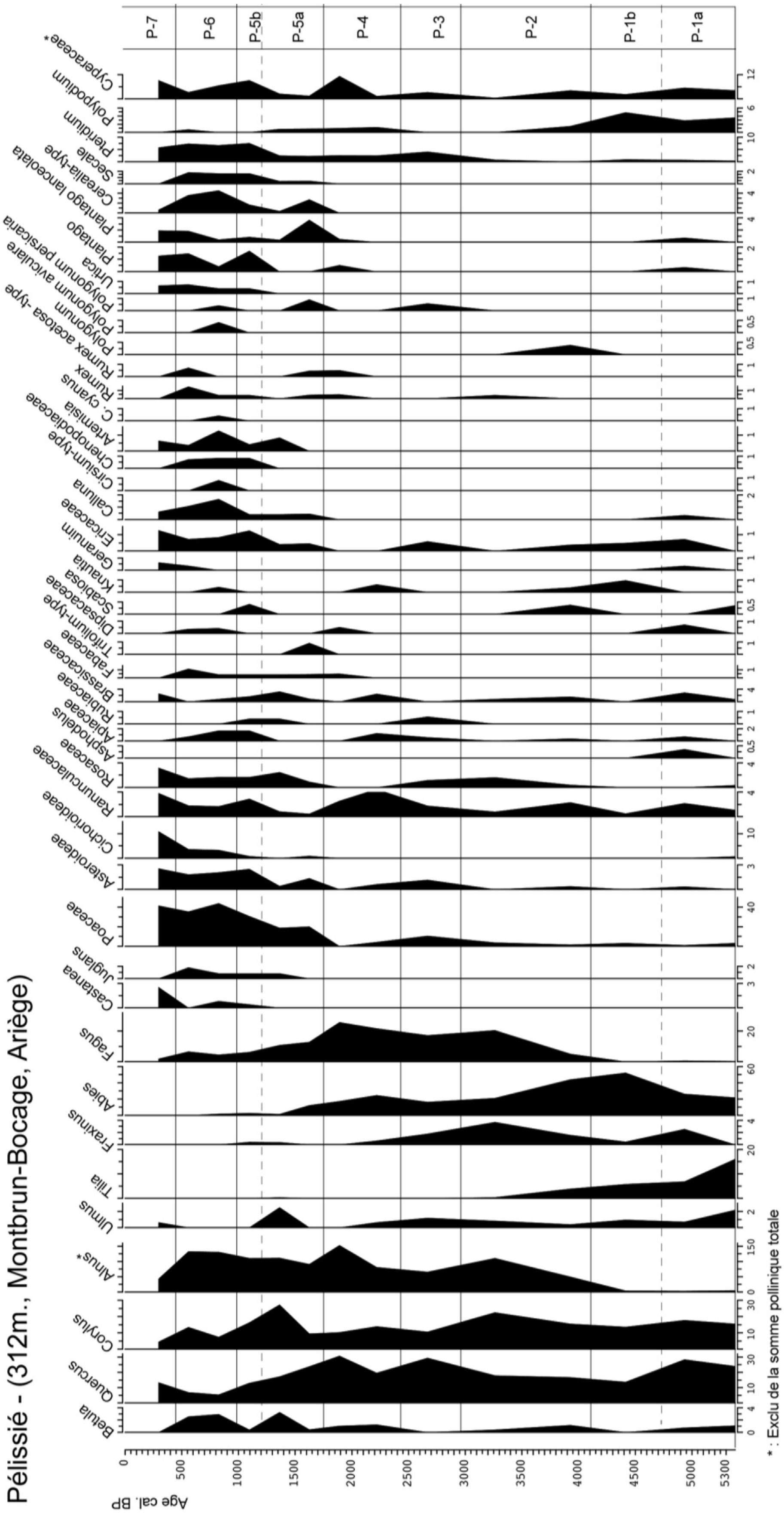

Fig. 7. Main taxa pollen diagram from the Pélissié peat bog.

to 3200 cal BP. These fires contrast with the increasing humidity, and were more likely induced by increasing human activity in the valley, indicated by the arrival in the pollen diagram of *Rumex* or *Polygonum*, which are related to grazing activities. The soil charcoals that were dated confirm this anthropization of the area, with clear impacts on *Abies*, the species represented in the two charcoals dated for this period. The question remains: Is the shift from *Abies* to *Fagus* natural and due to climate change or the product of some human impact? It is difficult to determine where natural causes end and human causes begin in the landscape changes during the second half of the Holocene. Many authors (Keller et al., 2002; Van der Knaap et al., 2004; Wick and Möhl, 2006; Kozáková, 2011) deduce a natural-climatic trend in the fir–beech relationship, which was affected by clearings maintained in order to carry out practices such as slash-and-burn agriculture or grazing activities. Other researchers (Kenla and Jalut, 1979; Jalut et al., 1982, 1988; Galop et al., 1994; Galop, 2005) have shown that the climate in the Pyrenees was an important factor for the development of beech forest, but they also demonstrate the human influence in the strong decline in fir forests. In this period, fir was totally destroyed by overexploitation in some eastern and central Pyrenean valleys (Galop and Jalut, 1994; Bonhôte, 1998).

Around 2700 cal BP, the pollen record shows us a time of change after a period of forest recovery. This change intensified during Antiquity. By about 2000 cal BP, the first agricultural indicators appeared and we could see clear effects of anthropization on the forests. All arboreal taxa decreased, except *Corylus* and *Juglans*, which first appeared at that point. During Late Antiquity, the simultaneous growth of anthropogenic indicators (*Plantago lanceolata*, *Rumex*, Asteraceae), cereals (Cerealia, *Secale*) and cultivated trees (*Juglans*), as well as the increase in *Poaceae*, provide strong evidence of increasing agrarian uses.

The soil charcoals confirmed this change and its effects on the fir forest. At the lower level (NI) of Montbrun2 (Fig. 5), fir was dominant; at the higher level (NII) it decreased, to be replaced by beech and other species indicative of forest clearings. *Juniperus* and *Abies* charcoals were dated at these levels (1800–1600 cal BP), which correspond precisely to the Roman period. Changes and decline in fir forests at that time were not a local phenomenon, occurred at various points in the mountains of south Europe and Pyrenees. The Alps are a clear example of the strong human pressure on the forests during the Roman period (Küster, 1994; Nakagawa et al., 2000; Ortu et al., 2003; Muller at al., 2007). According to the palaeobotanical records in the Pyrenees, this pressure was unequal in the different valleys (Esteban et al., 2003; Galop, 2005; Ejarque et al., 2009; Cunill, 2010; Galop et al., 2013). Part of this irregular distribution of human pressure was due to the localization of mining activity on both sides of the mountain range (Dubois, 1996, 2000; Camareo et al., 1998; Galop, 2005). The proximity of important Roman copper mines in the north Pyrenean Piedmont (Dubois and Guilbaut, 1982) offers a possible explanation for the agricultural intensification in the Montbrun area.

During the early Medieval period, human activity intensified. Pollen indicators show that the agrarian expansion that began during Antiquity underwent dramatic change. Arboreal taxa clearly declined, and at this point fir nearly disappeared from the pollen diagram. Charcoals dated to later periods show that the fir persisted, although to a lesser degree, in the vegetation assemblages of Montbrun and did not completely disappear from the north Pyrenean foothills. The acceleration of the anthropization of the Pyrenean mountains seems to be generalized in this period (Pèlachs, 2005; Rius at al., 2009; Bal, 2011; Galop et al., 2013; Rendu, 2013).

The accelerating human activity continued without pause during the late Middle Ages, with increasing and expanding indicators of agro-pastoral activity. The numerous charcoals dated to this period emphasize this landscape change and the expansion of fields and pastures. Nine of the 15 charcoals belong to this period and four of them are remains of fir. It is the period of strongest anthropization, which can be identified in most palaeoecological or historical sources in the Pyrenees. French demographic historians called this period “the full world” (Dubois, 1988) due to the high population density.

At this point, we must pose the question of which anthropic (land management) and/or environmental (climate, sunshine, soil) elements allowed the fir tree to survive to the present here, despite the same periods of maximum anthropization that the firs of the nearby lowlands did not survive. This is a topic for further research in the zone. The documentary information found to date (Cunill et al., 2014) does not provide accurate information about forest management until the 17th century. In 1667, Louis de Froidour “Great Commissioner of Forest Reformation”, described the nearby fir forest of Sainte-Croix-Volvestre as degraded and emphasized the need to preserve and increase fir forests, a useful resource of interest for the kingdom.

5.2. Inside the forest of Montbrun

The analysis of soil charcoals allowed us to study the woody assemblages at a more local scale, providing information on the different aspects of the valley slopes. Topography, climate, and land management were clearly variable and important in the configuration of the landscape, and our charcoal record provides good evidence of this situation.

The sampling point designated for analysis of the pedosedimentary zone downstream of the valley provided information about the vegetation dynamics but also about the geomorphologic dynamics. The sedimentary profile of Montbrun1 is defined by a pedological horizon 20 cm thick surmounting a 120 cm sedimentary settling (Fig. 5). At the base of this unit, there is a layer of decimetric pebbles and centimetric gravels supporting the river's course during wet seasons. Below this layer, grey clays rest on a limestone substratum. These deeper layers, the fruit of the first phases of erosion, contained charcoals of varying ages, ranging from 3500 cal BP to 670 cal BP. This indicates the beginning of major processes of erosion during the deforestation of the valley in the Middle Ages. The soils and colluvium of the whole watershed were reworked, including materials from the summit plateaus. Our discovery of a charcoal from the Medieval period under the cemented pebble layer confirms the Medieval chronology of this process. Dates from upper layers showed a chronological sedimentation with 12th and 13th century charcoals at levels VI and VII (80–110 cm) and 16th and 17th century charcoals at levels IV and II (10–70 cm). Altogether, these data indicate that 120 cm of colluvial sediments were deposited during the centuries following the medieval erosion, lasting at least until the end of the 17th century. Even if there were forest fires or pasture burnings during the Bronze Age, these would not have caused the massive soil erosion in the river basin. The fires and human activities in general, however, did have a major impact on the woodlands in the Late Middle Ages, intensifying after the 10th and 11th centuries and until the 15th century. We have many dates and pollen diagram indicators of human activity from this period; the erosion that deposited grey clays, large pebbles, gravels, charcoals, and large tree trunks also occurred during this period. This colluvial process after a major land clearing has been well documented and studied in Central Europe (Bork and Lang, 2003; Bork et al., 2009; Dreibrodt et al., 2009). Following this episode, a stabilization of sediments that constitutes the 120 cm unit occurred after the 14th–15th century. These materials came from the rapid, superficial erosion of the slopes that could have been caused by burning of pastures, cultivation of unstable terraced fields on the slopes, clear cutting, forest fires, etc. In the final period, soil erosion stopped and the small creek incised the whole sedimentary stratum.

Another important highlight of this profile is that *Abies* charcoals were found throughout. Although it is true that their quantity is small, their presence is constant. The oldest and newest dates in this profile were *Abies*, which illustrates the historical existence of this species at the heart of the Montbrun region.

The Montbrun2 sampling point shows that fir was of great importance in the composition of the forest, as more than 40% of charcoals at the base were *Abies*. At the upper level, other species appear that mark the clearing of the woodland (e.g., *Juniperus*, *Corylus*, *Prunus*, *Populus*) and *Abies* never recovered its higher percentages at any of the upper levels. The dates (*Abies and Juniperus*) from lower levels are from Antiquity, which corresponds to the time of fir decline on this site. At the upper levels we find the effects of this decline from the 15th to 17th centuries, the most recent periods for which we recorded dates.

The sunny slope offered some surprising results. At Montbrun3, an old, private woodland located close to fallowed lands and recent plantations, we expected to see a high percentage of charcoals as a result of forest clearing or slash-and-burn agriculture. However, the anthracomass we found was minimal and even non-existent at one of the levels. Despite this lack of charcoals, the result is valuable in terms of information about the sunny slope. For example, the Bronze Age (3170 ± 50 cal BP) dating in the lower level confirmed that the fir tree extended indifferently on all the slopes of the basin after the Neolithic, and likely until the Middle Ages. Today, fir is growing on the slope and abundant seedlings are visible in the undergrowth. In addition, the oldest evidence of forest fire (6900–6300 cal BP) was found in this place. The currently available data in Montbrun do not allow us to affirm that we have evidence of human impact, but other palaeoenvironmental data from the Pyrenean Piedmont (Rius et al., 2009) indicate this is a plausible hypothesis. In any case, this dating indicates an early sign of sunny slopes disturbance. There are several possible explanations for the absence of more recent dated fragments. First, we found only very small charcoal fragments, for the most part impossible to use for AMS carbon dating. Therefore, more recent charcoals could possibly have been present but we could not date them because of their size (<10 mg). Secondly, intense medieval or postmedieval erosion could have taken away the soil and the charcoals it contained. Finally, we hypothesize that, from the Bronze Age until very recent periods, this was a zone without a major impact from fires, because these spaces remained open clearings without woody vegetation after the Bronze Age. This hypothesis agrees with observations made about the end of the Iron Age (Rius et al., 2009). In conclusion, this absence of dated charcoals raises questions about very specific spaces, such as the sunny slopes of Pyrenean valleys.

The chronological stratification of soil charcoals is always a topic of discussion in any pedoanthracological study. Many previous studies have shown that we cannot simply assume that charcoal fragments will be time-stratified in the soil where we find them (Carcaillet, 2001; Bal, 2006). Studies in alpine and subalpine valleys of the Alps and Pyrenees reflect this reality (Carcaillet, 2001; Cunill et al., 2012, 2013), but others carried out in deeper soils have shown that there may be a certain kind of stratification. For example, Carcaillet and Talon (1996) suggest a possible interpretation of "assemblages" or collections of charcoals in the soil profile. The sampling points in the Montbrun forest soil were chronologically stratified, and we can infer certain logical assemblages linked to forest succession. In the pedosedimentary soil of Montbrun, the chronology follows a logical connection with the sedimentation process. Early in the colluvial process, after opening up the area, erosion dragged with it a great quantity of charcoals from the different periods represented in the soils of the river basin. Later on, constant, gradual erosion continued to deposit the charcoals chronologically. In any case, we must always question the relationship between the chronology and the locations of charcoals if we wish to understand how soil functions and how pedoanthracological data should be interpreted.

5.3. Biogeography and past, present, and future of Abies alba in the Pyrenees

Confirmation of the presence of *Abies alba* at low altitudes in the foothills of the northeast Pyrenees contributes valuable information to our knowledge of the expansion of this species in the Pyrenees during the Holocene. From the palaeoecological data, we know that fir colonization in the Pyrenees during the Holocene occurred gradually, from east to west, beginning with the onset of colonization in various geographical areas (Mardones and Jalut, 1983; Pèlachs, 2005). A first phase of colonization has been documented between 9500 and 8000 cal BP in the eastern part of the north slope of the Pyrenees (Jalut, 1974; Reille and Loewe, 1993; Esteban et al., 2003). Several thousand years later, the first *Abies* pollen data appear in the central part of the Pyrenees (6500–5000 cal BP) (Jalut, 1974; Jalut et al., 1988). The third and final phase is the arrival of fir in the far western Pyrenees (Irati), where it is clearly present 650–500 cal BP (Galop, unpub. data).

If we focus on the presence of *Abies* at low altitudes in the Pyrenees massif, the data are scant. Those from Volvestre provide the only evidence of its abundance in the northern foothills of the Pyrenees east of the Garonne river. Pollen data from sampling points in the western foothills, Gabarn (Rius et al., 2009), Col d'Ech (Rius et al., 2012), and Cuguron (Galop et al., 2000) clearly show the absence of fir below 600 m a.s.l. In addition, the Abies pollen frequencies recorded reflect only long distance transport. If we consider, along with this east–west expansion of *Abies*, the absence of pollen in the low mountains of the western zone and the Montbrun data, our only option is to support the hypothesis of a nucleus of *Abies* diffusion from the Mediterranean Pyrenees, where it was growing at low altitudes in 9000–8000 cal BP (Jalut, 1974; Reille and Loewe, 1993).

On the other hand, this difference between eastern and western populations of *Abies alba* on the northern slope of the Pyrenees is also supported by the genetic analysis performed by Fady and Musch (Gonin et al., 2012). Two genetic groups are described. One group consists of the populations from the Mediterranean Pyrenees to the Garonne valley, including the Volvestre fir woodlands. The second group extends from the Garonne valley to the Basque mountains (Irati). According to Fady, the most likely cause of this structure is the existence of at least two refuge areas, or two distinct groups of refuge areas, during the Wurmian glaciation. Each area would have evolved differently; together, they formed the basis of *Abies* postglacial recolonization in the Pyrenees.

The role of the Mediterranean lowlands as refuge areas is evident not only in the Pyrenean zone but also at the southern European level, as clearly shown in studies of the Italian peninsula (Terhürne-Berson et al., 2004; Liepelt et al., 2009). The palaeoecological data from Italy confirm the existence of firs in low-lying zones and areas near the sea during the mid-Holocene (Wick and Möhl, 2006; Colombaroli et al., 2007; Drescher-Schneider et al., 2007; Bellini et al., 2009). These populations at lower altitudes did not escape high levels of anthropization, an essential part of the reason we no longer find any residual population below 600 m altitude (Di Pasquale et al., 2014).

Palaeoecological data linked to topoclimatic modelling and to the study of residual populations lead us to question the paradigm of the fir as a species linked to cold and mountainous zones. Studies such as those by Tinner et al. (2013) and Di Pasquale et al. (2014) have shown the historical survival of firs in much more Mediterranean environments, far from the current paradigm. Residual populations such as the Volvestre forest provide current data that can help us understand the true ecological niche of *Abies alba*, which is much broader that what has been assumed to date. This new knowledge will allow us to anticipate the future dynamic of this species at this key time of climate change.

6. Conclusion

This research demonstrates the natural origin of the Volvestre fir woodlands, located at the lowest altitude in the Pyrenees. This clearly was not an isolated location; it provides evidence that fir had once successfully occupied all of the eastern Pyrenees lowlands, making these forests a natural heritage of the Pyrenees. Their natural origin is important at the biogeographic level because it provides information about the distribution and postglacial dynamics of fir populations secluded in Mediterranean areas during the mid and late-Holocene. It also confirms an ancient and important anthropization of the landscapes of the North Pyrenean foothills, an area where archaeological and palaeoecological data are very scattered, and sometimes non-existent. It is now possible to establish an initial chronology of human settlement and forest transformation; further studies are needed to validate the results.

The body of information available about the natural dynamics and the study of human intervention in this fir forest provides data that can help us understand the palaeoecological history of the forest. Even more important, it helps us understand the current *Abies alba* distribution in the Pyrenees and suggests possible future dynamics in the context of global climate change. The present study confirmed that pedoanthracology can be a useful methodology for interdisciplinary study of long-term dynamics of small-scale sites like ancient forests.

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